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ANNEX NO. 6

INTERNATIONAL SYSTEM OF UNITS

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The establishment of the international system of units, recommended for scientifical, technical, practical and teaching purposes, and whose basic units have been adopted in 1954 by the Tenth General Conference on Weights and Measures (Resolution No. 6), ends the preparatory phase of several years which was necessary to insure international uniformity in the field of units of measure. The scientifical and technical principles involved in the building of this system and the practical aspects of the problem are discussed hereafter.

auth abstr.

SCIENTIFICAL AND TECHNICAL PRINCIPLES INVOLVED IN THE BUILDING OF THE INTERNATIONAL SYSTEM OF UNITS. -

The establishment of the units of measure of physical quantities by means of a system of units, using a few fundamental units from which the others are derived as secondary units, is, taken as a base, the only rational means, justified by scientifical, technical and practical considerations, of defining the units of the various quantities.

The first system of units of measure was the metric system introduced in France at the end of the XVIIIth century. It consisted of a set of coherent units for the measurement of length, area, volume, capacity and mass, whose base rested on two fundamental units: the meter and the kilogram.

The notion of system of units of measure for a wide field of physical quantities was first introduced in 1832 by Gauss, who proposed a system based on three fundamental units (length, mass and time) and which he called "Absolute System of Units". Gauss chose, for the fundamental units of the proposed system the millimeter, the milligram, and the second.

Later on, there appeared several systems of units for physical quantities (the centimeter gram second (CGS) system adopted in 1881 by the

International Congress of Electricity; the meter kilogramforce second (M.Kf.S) system, which became widely used for technical purposes after the middle of the XIXth century; the meter kilogram second (M.K.S) system, proposed by Giorgi in 1901; the meter ton second (M.T.S) system, intorduced in 1919 by French legislation; etc,).

The use of several systems of units leads, in practice, to considerable difficulties arising from the problem of conversion of the numerical values of the measured quantities, of constants, etc... from one system to another; and from the introduction of a great number of conversion factors. It was therefore becoming necessary to choose a single system of units, the most rational possible, which could be recommended for use on an international level.

The construction of a rational system of units implies the resolution of the following special problems:

a) Elaboration of a system of independent physical equations relating all the quantities for which it is necessary to establish units of measure;

b) Analysis of the system of equations, and choice of the fundamental units of the system;

c) Formation of the secondary units;

d) Formation of multiples and sub-multiples of the units.

The system of physical equations, necessary for the formation of a system of units, must satisfy the following conditions: The equations of the system must be independent and compatible, each one containing at least two physical quantities; the system of equations must permit the choice of a system of units all of whose coefficients are dimensionless quantities.

It is necessary, for the choice of the fundamental units, to abide by the following conditions:

1) The certainty of coherence of the system of units, that is to say a choice of the fundamental units such that all secondary units may be derived by simple multiplication or division, without introduction of numerical coefficients;

2) The fundamental units must include those which it is possible to reproduce with the greatest accuracy;

3) The magnitude of the units (both fundamental and secondary) must be convenient for practical use.

While studying the problem of the construction of a system of mechanical units based on a system of physical equations relating the mechanical

quantities, it is possible to reach the conclusion that it would be possible to chose several systems of units whose base would rest on two or three units combined differently. For this reason, systems of the type L.T (in which the fundamental units are length and time), L.M.T (length, mass and time) or L.F.T (length, force and time), have been suggested.

Taking the above mentioned conditions into consideration, the analysis of these various systems leads to the conclusion that the L.M.T system is the most perfect. The system of the L.F.T type which is presently used for technical purposes is far less perfect. Reproduction of the unit of force is far less accurate than that of the unit of mass and, in this system, the secondary unit of mass is not a very convenient quantity.

For practical purposes, meter, kilogram, and second are the most convenient fundamental units of the system of the LMT type; this is why international organizations of metrology and standardization have chosen the MKS system.

Three fundamental units are not sufficient for the construction of the system in the field of heat measurements; it is necessary to add a fourth specific fundamental unit. This fourth quantity is temperature, and the calorific unit system is of the LMTθ type, where θ is temperature. The unit of temperature can be defined in several manners but the meter-kilogram-second-degree Kelvin system is the easiest and most rational as far as the magnitude of the fundamental units are concerned.

In the field of electric and magnetic measurements, it is possible to build a system of units using as a starting point the units of length, mass and time, and a unit of some electric or magnetic quantity. For practical purposes the system with the four fundamental units: meter, kilogram, second and ampere (MKSA system) is the most convenient. This system insures the necessary liaison with the mechanical units.

Acoustical measurements do not require additional fundamental units, and in this field all quantities can be expressed in the MKS system.

For measurements of light, three fundamental units are sufficient: those of length and of time, and a third specific unit: light intensity. That is why a system of the LTI type can be used for light measurements where I is the light intensity. In practice the system with the three fundamental units: meter, second and candle, is the most convenient.

For measurements in the field of ionizing radiations (X and γ rays and radioactivity), additional fundamental units are not necessary (except for one electrical unit) and the MKSA system can be used. The International Commission on Radiological Units and Measurements (ICRU) has established the dimensions and special names of the most usual secondary units, namely: amount of radiation, absorbed dose and activity (roetgen, rad and curie). For the

measurement of the amount of radiation in the MKSA system, the secondary unit is the coulomb per kilogram (C/kg); for the absorbed dose, it is the joule per kilogram; for activity, it is 1/s. The corresponding units adopted by the ICRU are the roentgen = 2.57976×10^{-4} C/kg; the rad = 0.01 J/kg; the curie = 3.7×10^{10} S^{-1}.

In order to include the entire field of physical phenomena in a single system of units of measure, the most rational system is the system based on six fundamental units: length, mass, time, thermodynamic temperature, current strength and light intensity. The most convenient magnitudes for the fundamental units of this system are those of the meter-kilogram-second-degree kelvin-ampere-candle system of units.

PREPARATION, ESTABLISHMENT AND PROPAGATION OF THE INTERNATIONAL SYSTEM OF UNITS.-

In 1913, Ch-Ed. Guillaume, Deputy-Director of the International Bureau, presented to the Fifth General Conference on Weights and Measures a report on systems of units, giving particular attention to the MKS system, and emphasizing the fact that it should be preferred to all other systems of units. Guillaume pointed out the fact that in the MKS system the units of work and power coincide with the same units in the practical absolute system of electrical units. Acting on this report, the General Conference invited the International Committee on Weights and Measures to continue the study of the question of the system of units.

In 1948, the International Union of Pure and Applied Physics submitted the following resolution to the Ninth General Conference:

a) The International Union of Pure and Applied Physics has decided to request from the International Committee on Weights and Measures that a practical international system of units be adopted for international relations. It does not recommand that the C.G.S system be abandonned by physicists.

b) The International Union of Pure and Applied Physics recommends for this purpose the system involving the meter the kilogram (mass), the second, and an electrical unit of the practical absolute system (to be decided upon in the near future).

c) The unit of force of this system (the force which, applied to a mass of one kilogram, gives it an acceleration of 1 m/s^2) is to be named newton.

Simultaneously, the French Government had presented to the General Conference a project of its own whose aim was the international unification of units of measure. The general considerations of the French proposition, established upon the advice of the National Scientific Permanent Bureau of Weights and Measures, were as follows:

1) The fundamental units of length, mass and time must be the meter, the kilogram (mass), and one second of solar mean time.

2) The absolute units of the practical electrical system as they are defined in the October 1946 resolutions of the International Committee on Weights and Measures, and as they are included at the present time in National legislations, must be preserved.

3) It is necessary to eliminate any system which includes a fundamental unit of force or of weight. Even if it seems advisable to authorize the use of a unit of weight for practical mechanics, a special name, not resembling the name of a metric unit of mass either by its expression or by its symbol, should be given to it.

The above project included the table of units of the M.K.S.A system and the drafts of legal documents and regulations concerning units of measure.

After discussion of the propositions presented, the Ninth General Conference (1948) adopted resolution No. 6 as follows:

The General Conference,

Considering that the International Committee on Weights and Measures has received a request from the International Physics Union, asking that it adopt a practical international system of units for international relations, and recommending to it the M.K.S system plus an electrical unit of the practical absolute system, and not recommending that the C.G.S system be abandonned by physicists;

Considering that it has received a similar request from the French Government, together with a project destined to be used as a base for discussions of the establishment of complete regulations regarding units of measure:

Instructs the International Committee to open an official investigation concerning the opinion of the scientific, technical and pedagogical circles of all countries (offering as a base the French document), and to conduct its investigation actively; to centralize the replies; and to submit recommendations concerning the institution of a single practical system of units of measure susceptible of being adopted by the signatory nations of the meter convention.

The study of this question in the various countries, and the dispatch of comments to the International Bureau of Weights and Measures, took more time than was expected, and the study of all the documents received was not completed at the time of the Tenth General Conference on Weights and Measures (1954).

After discussing the question of the International System of Units, the Tenth General Conference adopted the following resolution No. 6:

> As a result of the wish expressed by the Ninth General Conference in its resolution No. 6 concerning the institution of a practical system of units of measure for international relations, the Tenth General Conference on Weights and Measures, has decided to adopt as the basic units of this system, which remains to be established, the following units:
>
> | | |
> |---|---|
> | Length | meter |
> | Mass | kilogram |
> | Time | second |
> | Current strength | ampere |
> | Thermodynamic temperature | degree Kelvin |
> | Light intensity | candle. |

This resolution establishes a strong base for international unification of units of measure. At the same time (1954), the International Committee on Weights and Measures had created an internal "system of units commission" constituted by seven members of the Committee plus the director of the International Bureau.

From 1954 to 1956 the results of the investigation conducted in the different countries were studied according to the decision of the Ninth General Conference. The replies received from 21 nations indicated that the proposed project for unification of the systems of units of measure had been very much welcomed and that the comments concerned only details, especially about the legal part of the project.

In October of 1956, at the time of the International Committee meeting, during a meeting of the System of Units Commission, consideration was given to the results of the official investigation, and a study was made of drafts of an initial list of additional and secondary units established from the resolution on basic units of the Tenth General Conference.

A lengthy discussion was started when the question of a name for the system of units was raised. Of the three proposed variations: "Giorgi system", "M.K.S.A.°K.C system" (initials of the names of the six basic units of the system) and "International System of Units", the latter was unanimously adopted by the Commission for recommendation to the International Committee.

The Commission also adopted an initial list of units of the International System of Units, including two additional units and twenty-eight secondary units. This list was presented to the International Committee for approval.

On the 6th of October 1956, the International Committee examined the recommendation of the System of Units Commission, and adopted Resolution No. 3, which follows:

> Considering the instructions of the Ninth General Conference on Weights and Measures concerning the institution of a practical system of units susceptible of being adopted by all the signatory nations of the Meter Convention.
>
> Considering the whole of the documents sent by the twenty-one countries which have responded to the inquiry prescribed by the Ninth General Conference on Weights and Measures.
>
> Considering Resolution No. 6 of the Tenth General Conference on Weights and Measures determining the choice of the basic units of the system to be established:
>
> Recommends that the system based on the (six) basic units adopted by the Tenth General Conference be taken as the International System of Units.

Simultaneously the recommended list of additional and secondary units of the International System was adopted without prejudice to other units which could be added in the future.

During its 1958 meeting, the International Committee discussed, and took a decision concerning, the abbreviation to be used to designate the "International System of Units"; the abbreviation SI, formed of the initials of the words "International System", and utilizable in all languages, was adopted. In addition, in order to complete the list of prefixes already adopted for the formation of multiples and sub-multiples of the units, the International Committee gave its approval to the four prefixes tera and giga, nano and pico.

The designations of the secondary units of the International System of Units are proposed in accordance with international recommendations. As far as the unit of magnetic field is concerned, the adoption of the name "tesla" corresponds to a decision by the International Electrotechnical Commission (1956). At the present time, Technical Committee No. 24 of the C.E.I is studying a Russian proposal concerning the attribution of the name "lentz" to the unit of magnetic field intensity. Considering the fact that no decision has been reached up to now, this unit not yet have any particular name.

The introduction of the International System of Units based on the six fundamental units adopted by the Tenth General Conference on Weights and

Measures is an important step forward generalizing, as it does, the experience of the scientific and technical circles of various countries, and of the international organizations of metrology, of standardization, of physics and of electrotechnics.

In 1956, the International Standardization Organization (I.S.O) adopted the first international recommendation for standardization of the units of measure (I.S.O, R 31, part 1). In this recommendation, the system of units based on the six units adopted by the Tenth General Conference on Weights and Measures and temporarily labelled "M.K.S.A. system" is given the first place. The first table of this recommendation is that of the fundamental units of this system: meter, kilogram, second, ampere, degree Kelvin and candle.

In 1958, the International Committee of Legal Metrology adopted the following resolution concerning the International System of Units:

> The International Committee of Legal Metrology, meeting in plenary session on the 7th of October in Paris, has decided to adhere to the resolution of the International Committee on Weights and Measures concerning the establishment of the International System of Units (SI).
>
> The basic units of this system are: meter, kilogram, second, ampere, degree Kelvin and candle.
>
> The Committee recommends the adoption of this system by Member Nations of the Organization in their legislation on units of measure.

Since 1955, several countries have adopted, in their legislation or in their national standards, the system of units recommended by the International Committee on Weights and Measures under the name of International System of Units.

As a conclusion to the proceedings and recommendations about the establishment of a practical system of units of measure, the final decisions to be taken concern the ratification:

1) Of the name "International System of Units", and of the abbreviation SI, for the system based on the six fundamental units adopted by the Tenth General Conference (1);

2) Of the additional and secondary units of this system as recommended by the International Committee (see records C.I.P.M., 1956, 25, Resolution No. 3, page 83);

3) Of the list of prefixes approved by the International Committee for the formation of multiples and sub-multiples of the units (see records C.I.P.M., 1958, 26-A, page 89) (2).

([1]) The definitions of the basic units are those which have been approved by the General Conferences:

- meter and second (Eleventh Conference, 1960, Resolutions No. 6 and 9, pages 85 and 86);
- kilogram (Third Conference, 1901, page 70);
- ampere and candle (records C.I.P.M., 1946, 20, pages 132 and 121; Ninth Conference, 1948, pages 49 and 54);
- degree Kelvin (Tenth Conference, 1954, Resolution No. 3, page 79).

([2]) Note added to the proof: Items 1), 2) and 3) have been re-examined by the System of Units Commission which met at the "Pavillon de Breteuil" on the 6 of October 1960, and handed its report to the International Committee (records C.I.P.M., 1960, 28, fifth meeting). After discussion of the propositions submitted by the International Committee (see page 65), the Eleventh General Conference adopted Resolution No. 12, page 87.